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Precision tests of QED and non-standard models by searching photon-photon scattering in vacuum with high power lasers

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Abstract: We study how to search for photon-photon scattering in vacuum at present petawatt laser facilities such as HERCULES, and test Quantum Electrodynamics and non-standard models like Born-Infeld theory or scenarios involving minicharged particles or axion-like bosons. First, we compute the phase shift that is produced when an ultra-intense laser beam crosses a low power beam, in the case of arbitrary polarisations. This result is then used in order to design a complete test of all the parameters appearing in the low energy effective photonic Lagrangian. In fact, we propose a set of experiments that can be performed at HERCULES, eventually allowing either to detect photon-photon scattering as due to new physics, or to set new limits on the relevant parameters, improving by several orders of magnitude the current constraints obtained recently by PVLAS collaboration. We also describe a multi-cross optical mechanism that can further enhance the sensitivity, enabling HERCULES to detect photon-photon scattering even at a rate as small as that predicted by QED. Finally, we discuss how these results can be improved at future exawatt facilities such as ELI, thus providing a new class of precision tests of the Standard Model and beyond.

Keywords: Standard Model, Beyond Standard Model, Electromagnetic Processes and Properties.

Contents

1. Introduction

Photon-Photon Scattering (PPS) in vacuum is a still unconfirmed prediction of both Quantum Electrodynamics (QED) [1] and non-standard models such as Born Infeld theory [2, 3]. Additional contributions to the process can also appear in new physics scenarios involving minicharged [4] or axion-like [5] particles. However, all the experiments that have been performed by now could only be used to set upper limits on the photon-photon cross section $\sigma_{\gamma\gamma}$. The best constraints were obtained recently by PVLAS collaboration [6], and are still seven orders of magnitude above the QED prediction for $\sigma_{\gamma\gamma}$. In the last few years, there has been an increasing interest in studying the possibility to detect PPS at future facilities, using two possible strategies. On one hand, the cross section for the process will be maximum at a possible future photon-photon collider [7], based on a free electron laser producing two beams of photons in the MeV range. A second approach will be to perform experiments at optical wavelengths, and compensate the smaller cross sections with a very high density and/or a long path of interaction of the colliding photons [8, 9, 10, 11]. Most of these proposals require the construction of new facilities, that will eventually be available in the future, such as a free electron laser and/or an exawatt laser. Two exceptions are Refs. [10, 11], that discussed the possibility of performing experiments at present facilities to improve the PVLAS limit on the photon-photon cross section. However, even in these cases the predicted sensitivity was found to be sufficient to detect PPS of QED origin only at future facilities, such as ELI [12] or VIRGO+ [13], respectively.

Here, we will propose a set of experiments that can already be performed at present petawatt laser facilities, such as HERCULES [14, 15]. First, we perform a new theoretical computation to get a quantitative expression for the phase shift that is produced by PPS when two orthogonally polarised beams cross each other. This result turns out to provide a test for PPS of QED origin which is significantly more sensitive than our previous proposal [9, 10], in which the two crossing beams had the same polarisation. Moreover, it can be used in combination with our previous result to provide a full test of all the parameters appearing in the low energy effective Lagrangian describing the photons in non-standard models, such as Born Infeld theory and scenarios involving minicharged (MCP) or axion-like (ALP) particles. In fact, taking into account the precision that can be achieved in the measurement of optical phase shifts or ellipticities [16, 17, 6], we propose a set of experiments that will allow either to detect PPS at HERCULES, or to set new limits on the relevant parameters, improving by several orders of magnitude the current constraints obtained by the PVLAS collaboration. We then propose a multi-cross optical mechanism that can further improve the sensitivity of this set of experiments, eventually enabling HERCULES to detect PPS as predicted by QED. Finally, we discuss how these results can be improved at future exawatt facilities such as ELI, thus providing a new class of precision tests of the Standard Model and beyond.

2. The effective Lagrangian for the electromagnetic fields in QED and in non-standard models

We will consider the case of photon energies well below the threshold for the production of electron-positron pairs, and assume an effective Lagrangian for the electromagnetic fields $\mathbf{E}$ and $\mathbf{B}$ of the form

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + \frac{7}{4}\xi_T \mathcal{G}^2, \tag{2.1}$$

being $\mathcal{L}_0 = \frac{\epsilon_0}{2}\left(\mathbf{E}^2 - c^2\mathbf{B}^2\right)$ the Lagrangian density of the linear theory, $\mathcal{G} = \epsilon_0 c(\mathbf{E}\cdot\mathbf{B})$ and ϵ_0 and c the dielectric constant and the speed of light in vacuum, respectively. The additional, non-linear terms, that appear multiplying the parameters ξ_L and ξ_T in equation (2.1), are the only two Lorentz-covariant terms that can be formed with the electromagnetic fields at the lowest order above $\mathcal{L}_0$. Therefore, they will appear as the first correction to the linear evolution both in QED and in non-standard models.

In fact, in QED photons can interact with each other through the interchange of virtual charged particles running in loop box diagrams [1]. Besides other interesting effects [18], such an interaction leads to the Euler-Heisenberg effective Lagrangian density [19], that coincides with equation (2.1) with the identification $\xi_L^{QED} = \xi_T^{QED} \equiv \xi$, being

$$\xi = \frac{8\alpha^2\hbar^3}{45 m_e^4 c^5} \simeq 6.7\times 10^{-30}\frac{m^3}{J}. \tag{2.2}$$

On the other hand, in Born-Infeld theory [2], we would obtain the relation $\xi_T^{BI} = 4\xi_L^{BI}/7$ [3], in general without a definite prediction for the numerical value.

The presence of a minicharged (or milli-charged) particle (MCP) [4] would provide an additional contribution analogous to that from the electron-positron box diagram. If the new MCP are spin 1/2 fermions, and assuming that their mass m_ϵ is still larger than the energy of the photons (the eV scale in optical experiments), we would obtain

$$\Delta\xi_L^{\rm MCP} = \Delta\xi_T^{\rm MCP} = \left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi, \tag{2.3}$$

where ϵ is the ratio of the charge of the particle with respect to the electron charge. The existing laboratory bounds in this regime is $\epsilon \lesssim 8\times 10^{-5}$ [4]. Taking masses above the eV scale, in order to apply the effective Lagrangian approach, this limits can be read as $\Delta\xi_L^{\rm MCP} \lesssim o(10^6\xi)$. As we shall see in the next sections, this constraint has been improved by PVLAS collaboration, and can be further strengthened by the experiments that we propose in the present paper. Of course, in this case there are already stronger limits, $\epsilon \lesssim 10^{-15}$, from astrophysical and cosmological observations [4]. A larger contribution might be obtained if the MCP are lighter than the energy scale of the photons (the eV scale in the present paper). However, this case would deserve a different treatment which goes beyond the purposes of the present work, since it cannot be described simply by an effective Lagrangian of the form of equation (2.1).

Similar considerations apply if the new MCP is a spinless boson. Assuming again that its mass m_ϵ is still larger than the energy of the photons (the eV scale in optical experiments), and using the results of Ref. [20], we would obtain

$$\Delta\xi_L^{\rm MCP0} = \frac{7}{16}\left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi \tag{2.4}$$

and

$$\Delta\xi_T^{\rm MCP0} = \frac{1}{28}\left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi. \tag{2.5}$$

On the other hand, if the MCP is a spin 1 boson, the contribution to the effective Lagrangian would be larger, as computed using the result of Refs. [20]. We obtain

$$\Delta\xi_L^{\rm MCP1} = \frac{261}{16}\left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi \tag{2.6}$$

and

$$\Delta\xi_T^{\rm MCP1} = \frac{243}{28}\left(\frac{\epsilon\, m_e}{m_\epsilon}\right)^4 \xi \tag{2.7}$$

Let us now discuss the case of an axion-like particle [5]. This can be a Light Pseudoscalar Boson or a Light Scalar Boson, depending on the coupling with the photons, that is described in the Lagrangian density by the terms $\mathcal{L}_P = -\sqrt{\hbar\, c}\, g_P \Phi_P \mathcal{G}$ and $\mathcal{L}_S = -\sqrt{\hbar\, c}\, g_S \Phi_S \mathcal{L}_0$, respectively. We can find the leading contribution to the effective Lagrangian when the photon energy is much smaller than the m_Φ scale, that can be cast in the form of equation (2.1) with an additional contribution given by

$$\Delta\xi_T = \frac{2\hbar^3 g_P^2}{7c\, m_\Phi^2} \tag{2.8}$$

and $\Delta\xi_L = 0$, in the case of pseudoscalars, or

$$\Delta\xi_L = \frac{\hbar^3 g_S^2}{2c\, m_\Phi^2} \tag{2.9}$$

and $\Delta\xi_T = 0$, in the case of scalars. On the other hand, for $m_\Phi \gtrsim 1$eV, the Cristal Ball [5] laboratory limit $g_P \leq 4.2 \times 10^{-3}$GeV^{-1} gives the contraint $g_P/(m_\Phi c^2) \lesssim 4 \times 10^6$GeV^{-2}, which can be converted in the limit $\Delta\xi_T \lesssim 2.2 \times 10^{-25} m^3/J$. This constraint has been improved recently by the PVLAS consideration [6], as we shall see in the next section. Again, the astrophysical limits $g_P \lesssim 2.7 \times 10^{-9}$GeV^{-1}, valid for $m_\Phi \lesssim 1$KeV [5], is still much more stringent than any laboratory bound.

Similar considerations apply for scalar boson, for which the best laboratory constraints are also those that were recently set by PVLAS, that we will review in the next section. We also recall that our approximations do not apply for masses smaller than the order of the energy of the colliding photons. In this case, the computation of $\Delta\xi_L$ is more complicated, and the production of real axions has also to be taken into account. The latter can be expected to produce dichroism, just as in the presence of a constant external magnetic field [21, 6], and combined with the measurement of ellipticity may allow for a determination of both m_Φ and $g_{S,P}$. However, this case lies beyond the scope of the present paper, that uses a phenomenological approach that can be applied to any theory that goes beyond the Standard Model, in the energy regime in which it only implies a different contribution to equation (2.1), as parametized by artitrary ξ_L and ξ_T. Expressing the electromagnetic fields in terms of the four-component gauge field $A^\mu = (A^0, \mathbf{A})$ as $\mathbf{B} = \nabla \wedge \mathbf{A}$ and $\mathbf{E} = -c\nabla A^0 - \frac{\partial \mathbf{A}}{\partial t}$, this gives the equations of motion as the variational derivatives $\delta\Gamma/\delta A^\mu = 0$, where $\Gamma \equiv \int \mathcal{L} d^4x$ is the effective action. Such equations are similar to the modified nonlinear Maxwell's equations that have been obtained in Ref. [22], the only difference being the distinction between ξ_L and ξ_T.

3. Present constraints

The current limits on PPS in vacuum have been obtained recently by the PVLAS collaboration [6] by searching evidence of birefringence of the vacuum in a uniform magnetic field background [21]. Their negative result was used to set the current constraints on the parameters appearing in equation (2.1). With our notation, their 95 % C.L. limit reads

$$\frac{|7\xi_T - 4\xi_L|}{3} < 3.2 \times 10^{-26} \frac{m^3}{J}. \tag{3.1}$$

Assuming $\xi_L = \xi_T \equiv \xi^{exp}$ as in QED, their results can be translated in the limit $\xi^{exp} < 3.2 \times 10^{-26} m^3/J$, which is 4.6×10^3 times higher than the QED value of equation (2.2) (7 orders of magnitude for the cross section $\sigma_{\gamma\gamma}$).

Note however that PVLAS experiment was only sensitive to the combination $|7\xi_T - 4\xi_L|$ of the parameters. In particular, this quantity vanishes when $\xi_T = \frac{4}{7}\xi_L$, therefore PVLAS experiment is unable to set any constraint on a pure Born Infeld theory.

4. Approximate solution for the scattering of orthogonally polarised beams

In Ref. [9], we have studied the scattering of two counter-propagating waves that are polarised in the same direction, and we have found that the effect of PPS was to produce a phase shift in each wave, which was proportional to ξ_L multiplied by the intensity of the other wave. That result was obtained by an analytical, variational approximation, and was shown to agree with a numerical solution of the full non-linear equations, that was also obtained in the second of Refs. [9].

Here, we will apply a similar variational method to find a solution for the problem of the scattering of two orthogonally polarised counter-propagating waves, one of which represents an ultra-high power beam. Let the low power and the high power waves be polarised in the x and y directions respectively, so that their linear (free) evolution (neglecting photon-photon scattering) would be $A_x(t,z)^{\rm lin} = \alpha_0 \cos(kz - \omega t)$ and $A_y(t,z)^{\rm lin} = \mathcal{A}\cos(kz + \omega t + \varphi)$, where $\omega = kc$ and we allow for an initial phase difference φ. Their energy density, when each of the two waves is taken alone, would be $\rho_x = \epsilon_0 \omega^2 {\alpha_0}^2/2$ and $\rho_y \equiv \rho = \epsilon_0 \omega^2 \mathcal{A}^2/2$, respectively. Hereafter, we will assume that $\rho_y \gg \rho_x$. When these two waves are made to scatter, they will affect each other due to PPS, as described by the non-linear terms in equation (2.1). First, we note that the assumption of no dependence on x and y of the fields guarantees that the condition $A_t = A_z = 0$ is maintained by the non-linear evolution, since we have checked that in this case the equations $\delta\Gamma/\delta A_t = 0$ and $\delta\Gamma/\delta A_z = 0$ are automatically satisfied, independently on the values of $A_x(t,z)$ and $A_y(t,z)$. Therefore, in the absence of x and y dependence, the components A_t and A_z with will not be generated if they are not present from the beginning. Second, we note that the non-linear effect is driven by the very small parameters ξ_L and ξ_T. This justifies a perturbatively-motivated variational approach, similar to that introduced in Refs. [9]. We then need to chose a good ansatz for the fields $A_x(t,z)$ and $A_y(t,z)$. In principle, each of the two components can get a transmitted wave contribution, propagating along the same direction as the original wave, and a reflected wave propagating in the opposite direction. In a perturbative approach, we can compute these different effects separately and then sum them up. Therefore, we will first neglect the reflected waves, and use the following ansatz:

$$\begin{aligned} A_x &= \alpha(z)\cos(kz - \omega t) + \beta(z)\sin(kz - \omega t), \\ A_y &= \mathcal{A}\cos(kz + \omega t + \varphi). \end{aligned} \tag{4.1}$$

Here, we have neglected the effect of the low power wave on the high power wave, taking into account that such an effect is expected to be proportional to the energy density of the low power beam. This expectation, inspired by our previous work [9], will be confirmed by the result that we will obtain below.

We now substitute the ansatz (4.1) in the Lagrangian (2.1), and average out the fast variation in z over distances of the order $2\pi/k$, assuming that the envelop functions $\alpha(z)$ and $\beta(z)$ will show a much slower variation, as we will verify a posteriori. We then compute the variational equations $\delta\Gamma/\delta\alpha = 0$ and $\delta\Gamma/\delta\beta = 0$, keeping the lowest order terms in the expansion parameter ξ_T and neglecting the higher order space derivatives $(d/dz)^n$ of $\alpha(z)$

and $\beta(z)$, as compared with k^n. After a long but straightforward algebra, we find the following equations:

$$\begin{aligned} \beta'(z) + \chi_T \alpha(z) = 0, \\ \alpha'(z) - \chi_T \beta(z) = 0, \end{aligned} \tag{4.2}$$

where $\chi_T \equiv 7\epsilon_0 c^2 \mathcal{A}^2 k^3 \xi_T/2$. Assuming the initial condition $\alpha(0) = \alpha_0$, $\beta(0) = 0$, in such a way that the corrected solution coincides initially with that of the linear problem, we find then $\alpha(z) = \alpha_0 \cos(\chi_T z)$, $\beta(z) = -\alpha_0 \sin(\chi_T z)$. After substituting in equation (4.1), we finally get the following variational solution:

$$\begin{aligned} A_x = \alpha_0 \cos(kz + \chi_T z - \omega t), \\ A_y = \mathcal{A} \cos(kz + \omega t + \varphi). \end{aligned} \tag{4.3}$$

In other words, taking into account that $\epsilon_0 \mathcal{A}^2 \omega^2/2 \simeq \rho$ is the energy density of the high power wave, we find that after a crossing distance Δz, the phase of the orthogonal, low power wave is shifted by an amount $\Delta\phi_T = \chi_T \Delta z = 7\xi_T \rho k \Delta z$. Note that this result is independent of the initial phase difference φ between the two crossing waves.

Let us now introduce the possibility that a reflected wave is generated in the component A_x, as described by the ansatz

$$\begin{aligned} A_x = \alpha_0 \cos(kz + \chi_T z - \omega t) + \gamma(z) \cos(kz + \omega t) + \delta(z) \sin(kz + \omega t), \\ A_y = \mathcal{A} \cos(kz + \omega t + \varphi) \end{aligned} \tag{4.4}$$

After repeating the same procedure as above, we get the following variational solution

$$\begin{aligned} \gamma(z) = \tfrac{\alpha_0 k z}{4\pi} \left[\cos(14\pi\rho\xi_T) - 1\right], \\ \delta(z) = \tfrac{\alpha_0 k z}{4\pi} \sin(14\pi\rho\xi_T). \end{aligned} \tag{4.5}$$

Now, the quantity $14\pi\rho\xi_T$ can be estimated for the petawatt laser HERCULES [15] that we will consider below for our proposals of experiments. In this case, the peak intensity is $I \sim 2 \times 10^{22} W cm^{-2}$ [15], corresponding to an energy density $\rho \sim 6.7 \times 10^{17} J m^{-2}$. Taking into account the PVLAS limit $\xi^{exp} < 3 \times 10^{-26} m^3/J$, and assuming that it can be applied to ξ_T at least roughly (see also figure 2 in the last section), we find that $\xi_T \rho \lesssim 2 \times 10^{-8}$ for the product giving the importance of the nonlinear QED effects. As a result, the variational solution for γ and δ implies that $\gamma(z) \simeq 0$ for all the practical purposes, and $\delta(z) \simeq 7\alpha_0 \rho \xi_T k z/2$. Taking $k \sim 7.8 \times 10^6 m^{-1}$ as for the wavelengths of e.g. the HERCULES laser ($\lambda = 800 nm$), we obtain that the $|\delta(z)/\alpha_0| \lesssim 0.5z/1m$. Now even in the multi-cross configuration that will be discussed below the crossing length will be smaller than the centimetre scale, so that $\delta(z)$ will be smaller than the low power amplitude α_0 at least by two orders of magnitude. For this reason, it will be neglected.

Finally, let us introduce the possible reflected wave in the component A_y, as described by the ansatz

$$\begin{aligned} A_x = \alpha_0 \cos(kz + \chi_T z - \omega t), \\ A_y = \mathcal{A} \cos(kz + \omega t + \varphi) + \eta(z) \cos(kz - \omega t) + \sigma(z) \sin(kz - \omega t). \end{aligned} \tag{4.6}$$

By repeating the same kind of computations and arguments as above, we find the following solution

$$A_x = \alpha_0 \cos(kz + \chi_T z - \omega t), \qquad (4.7)$$
$$A_y = \mathcal{A}\cos(kz + \omega t + \varphi) + \eta_0 \cos(kz + \chi_L z - \omega t),$$

where $\chi_L = 2\epsilon_0 c^2 \mathcal{A}^2 k^3 \xi_L = 4\xi_L \rho k$, $\eta(0) = \eta_0$ and we assume that $\sigma(0) = 0$. We then see that the counter-propagating wave in the y polarisation only exists if it is present from the beginning, and that it gets a phase shift $\Delta\phi_L = \chi_L \Delta z$ which is equal to that obtained in Ref. [9], as could be expected.

equation (4.7) implies that, after crossing a counter-propagating, linearly polarised ultra-intense laser pulse, an ordinary laser pulse is phase shifted both in the polarisations parallel and orthogonal to that of the high power beam. The corresponding phase shifts are

$$\Delta\phi_L = 4\xi_L \rho k \Delta z = 4\xi_L I k \tau, \qquad (4.8)$$
$$\Delta\phi_T = 7\xi_T \rho k \Delta z = 7\xi_T I k \tau,$$

where $I = \rho c$ is the intensity of the high power beam and $\tau = \Delta z / c$ is its time length. If we assume $\xi_L = \xi_T$ as in QED, we see that $\Delta\phi_T$ is more sensitive by a factor 7/4 than $\Delta\phi_L$ to the effect of PPS. This is already an improvement with respect to Ref. [9]. Moreover, the dependence of equations (4.8) on both parameters ξ_L and ξ_T will permit a full analysis of the effective Lagrangian (2.1), distinguishing between QED and other models such as Born Infeld theories. Finally, we note that (4.8) also implies that the high power pulse behaves like a birefringent medium, producing a relative phase shift $\Delta\phi_b = \Delta\phi_T - \Delta\phi_L = (7\xi_T - 4\xi_L) I k \tau$ between the transverse an parallel polarisations of the low power beam.

5. Proposal of experiments

We will now discuss how the result of equations (4.8) can be used to search PPS in vacuum by measuring phase shifts and ellipticities. In fact, Ref. [16, 17] provides a technique that allows for the measurement of phase shifts as small as $10^{-8} rad$, which is the noise limit [17]. This precision, that holds for ultra-short laser pulses [16, 17], applies then to our $\Delta\phi_L$ and $\Delta\phi_T$. A similar sensitivity can be obtained for the measurement of the ellipticity induced by $\Delta\phi_b$ corresponding to birefringence. In particular, in the same experiment that we have cited above [6], the PVLAS collaboration was able to resolve the corresponding $\Delta\phi_b$ with a statistical error $\sigma_b = 1.1 \times 10^{-8} rad$, thus allowing them to set a 95% C.L. experimental limit $\Delta\phi_b < 2.8 \times 10^{-8} rad$. Hereafter, to be definite and for simplicity, we will use this same numerical value, $2.8 \times 10^{-8} rad$, for the sensitivity in the measurement of $\Delta\phi_L$ and $\Delta\phi_T$, taking into account that the actual experimental precision will be close to this choice [16, 17].

We can now propose a set of three experiments:

1) A linearly polarised low power laser pulse is divided by a beam splitter in two branches. One of them propagates freely in vacuum, while the other crosses a contra-propagating ultra-high power laser pulse polarised in the same direction. The phase shift suffered by the low power pulse as a consequence of PPS is then measured by comparing with the pulse that has propagated freely, using the technique described in Ref. [16, 17]. Due to equation (4.8), this configuration can be used to measure the parameter $\xi_L = \frac{\Delta\phi_L}{4FIk\tau}$, where we have introduced a gain factor F that corresponds to a multi-cross configuration as discussed below. This experiment will then allow either to detect PPS by measuring a non-vanishing ξ_L, or to set an upper limit on this parameter as

$$\xi_L < \frac{2.8 \times 10^{-8}}{4FIk\tau}. \tag{5.1}$$

2) The configuration is the same as in case 1), except that now the high power beam is polarised in a direction orthogonal to that of the low power pulse. Due to equation (4.8), this setup can be used to obtain the parameter $\xi_T = \frac{\Delta\phi_T}{7FIk\tau}$ by measuring the phase shift $\Delta\phi_T$. This will allow either to detect PPS or to set the upper limit

$$\xi_T < \frac{2.8 \times 10^{-8}}{7FIk\tau}. \tag{5.2}$$

3) The low power beam polarisation has two components, one parallel and another orthogonal to that of the contra-propagating high power pulse. Ellipticity measurements can then be used to deduce the difference of the phase shifts $\Delta\phi_T - \Delta\phi_L = \Delta\phi_b$, allowing to determine the combination $\frac{7\xi_T - 4\xi_L}{3} = \frac{\Delta\phi_b}{3FIk\tau}$, thus allowing either to detect PPS, or to set the upper limit

$$\frac{|7\xi_T - 4\xi_L|}{3} < \frac{2.8 \times 10^{-8}}{3FIk\tau}. \tag{5.3}$$

The combination of these three experiments will permit a complete exploration of the parameter space. Actually, it is easy to see that if ξ_L and ξ_T have the same sign, as in QED and Born Infeld theories, experiment 3) is less sensitive than the combination of the others and can be discarded without losing significant information. On the other hand, if ξ_L and ξ_T have opposite sign, experiment 3) is the most sensitive one, although even in this case the other two measurements would be useful for a full determination of both ξ_L and ξ_T.

From equations (5.1), (5.2) and (5.3), we see that the sensitivity depends on the combination $Ik\tau$ of the experimental parameters of the ultra-high power laser beam, and on a gain factor F that will be discussed later. Therefore, the most favourable experimental configuration will be that allowing for the maximum value of the product $Ik\tau$. As far as we know, the highest value achieved at present facilities is that of HERCULES laser [15], that reaches peak intensities $I = 2 \times 10^{22} W/cm^2$, for a time length $\tau = 3 \times 10^{-14} s$ and wavelength $\lambda = 2\pi/k = 8.1 \times 10^{-7} m$. This gives $Ik\tau = 4.7 \times 10^{19} J/m^3$. Even in the absence of any gain factor ($F = 1$), such a facility will be able to resolve ξ_L and ξ_T as small as $1.5 \times 10^{-28} m^3/J$ and $8.6 \times 10^{-29} m^3/J$, respectively, thus allowing either to detect PPS of non QED origin, or set limits on the parameters that are more than two orders of magnitude (5 order of magnitude in the cross section) more stringent than the current PVLAS

limits, in addition to the fact that they constrain the full parameter space, including the case of Born-Infeld theories, that were unconstrained by PVLAS.

A significant improvement will be obtained in the near future at ELI [12], that in its first stage will achieve peak intensities $I \simeq 10^{25} W/cm^2$, for a time length $\tau \simeq 10^{-14} s$ and wavelength $\lambda = 2\pi/k \simeq 8 \times 10^{-7} m$. This gives $Ik\tau \simeq 8 \times 10^{21} J/m^3$. Even in the absence of any gain factor ($F = 1$), such a facility will be able to resolve ξ_L and ξ_T as small as $9 \times 10^{-31} m^3/J$ and $5 \times 10^{-31} m^3/J$, respectively. In particular, ELI would allow for the detection of PPS of QED origin and for measuring the parameter ξ with two figures.

6. Improving the sensitivity with multiple crossing

The sensitivity of our proposed experiments can be enhanced by making the two beams cross each other several times, using a kind of wave guide consisting of two parallel series of parabolic mirrors as shown in figure 1. An advantage of using parabolic mirrors is that, in the paraxial approximation, they do not generate aberrations in the beam. We assume that the laser pulses are localised at a distance R half a way to the path leading to the next mirror. To be concrete, we will also assume that at the crossing points the high power laser is focused to the diameter $d \simeq 0.8\mu m$ and intensity $I \simeq 2 \times 10^{22} W cm^{-2}$ of the HERCULES beam. The time duration $\tau = 30 fs$ implies that the pulse length $c\tau \simeq 9\mu m$ along the direction of propagation is approximately an order of magnitude greater than its transversal width, therefore the two beams must cross forming an angle θ close to π in order to maximize their superposiposition. These requirements may be achieved using plasma mirrors [23], that can work e.g. at the intensity $I_{\text{mirror}} \simeq 2 \times 10^{19} W/cm^2$ with a reflection coefficient $r \simeq 0.98$ [23]. In this case, the high power beam at the mirror should have a diameter equal to $d\sqrt{I/I_{\text{mirror}}} \simeq 25\mu m$. In order to avoid diffractive distortions, we will use parabolic mirrors of, say, a double diameter, $d_{\text{mirror}} \simeq 50\mu m$. On the other hand, the two planes are assumed to be at a distance $\simeq 2R$, with R much larger than d_{mirror}, say $R = 5cm$, in such a way that $\theta - \pi = 2\arccos(d_{\text{mirror}}/R) - \pi \simeq -2 \times 10^{-3}$, so that θ is very close to π. A serious technological challenge to be faced will be the very precise alignment of the mirrors, since any uncertainty in the direction will be multiplied by the number of times the beams are reflected. In principle, the orientation of the mirrors can currently be fixed with a precision as small as $\Delta\theta \sim 10^{-8} rad$ [24]. After N reflections, this will produce an uncertainty $\sim NR\Delta\theta$ on the position of the spot at the focus. This uncertainty must be smaller than the diameter of the beams at the focus, so that $N \lesssim d/(R\Delta\theta) \sim 10^3$.

In order to compute the gain factor F of this configuration, we note that after each reflection the intensity is reduced by a factor $r \simeq 0.98$. Moreover, the phase shift is due to the counter-propagating components of the photon momenta, $p_z = \hbar k \sin(\theta/2)$. Taking into account that k appears to the third power in the expression of the phase shift (or equivalently that it appears to the sixth power in the cross section [1]), the gain factor is then $F = \sin^4(\theta/2) \sum_{n=0}^{N+1} r^n$, where we have included a further factor $\sin(\theta/2)$ taking into account that Δz becomes $c\tau \sin(\theta/2)$ in this configuration. This result can also be obtained in more elegant and rigorous way by making the computation in the reference system in which the total momentum is zero and the two colliding photons are

antiparallel. In fact, by indicating with a prime the quantities in such a system, and being z and y the vertical and horizontal directions in thelaboratory system of figure 1, we have: $t' = \gamma(t - \beta y/c)$, $y' = \gamma(y - \beta ct)$, $z' = z$, $\omega' = \gamma(\omega - \beta c k_y)$, and $k'_y = \gamma(k_y - \beta\omega/c) \equiv 0$ and $k'_z = k_z$, where $\beta = ck_y/\omega$ and $\gamma = \sqrt{1-\beta^2}$. It is then easy to see that the phase $k'_z z' - \omega' t' + 2\epsilon_0 \mathcal{A}^2 (k'_z)^3 \xi_L \Delta z'$, when translated to the laboratory system, gives $k_z z + k_y y - \omega t + \Delta\phi$, with $\Delta\phi = \sin^4(\theta/2)\Delta\phi_{\theta=\pi}$. A similar result can be obtained in the case of orthogonally polarized waves.

Taking $N = 1000$ in the expression of F that we have obtained above, we can find a limiting value $F_{\max} \simeq 50$, that in principle can be achieved with present technology. As a result, the measurement of the phase shifts in the experiments 1) and 2) that we proposed above with such a gain factor will be able to resolve ξ_L and ξ_T as small as $3.0 \times 10^{-30} m^3/J$ and $1.7 \times 10^{-30} m^3/J$ respectively, thus allowing to detect PPS as predicted by QED, or find a signal of non-standard physics. Note that the combination of the two experiments will also be able to test Born Infeld theory and scenarios involving MCPs or axion-like particles, taking into account the discussion of section 2.

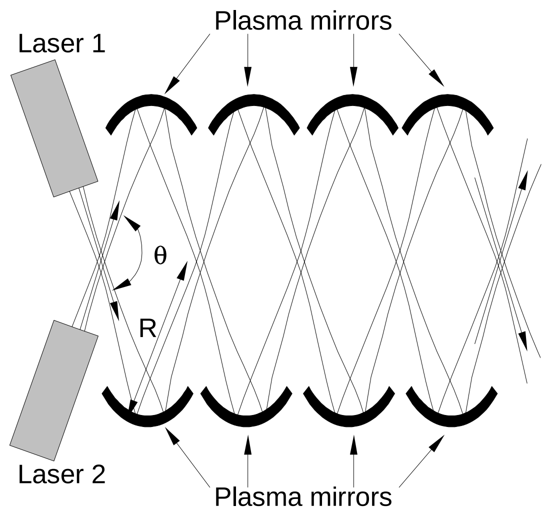

Figure 1: Proposed setup for multiple crossing of the two scattering laser pulses.

7. Conclusions

We have computed the phase shifts affecting a low power laser beam that crosses an high power laser pulse with general transverse polarisation, and proposed a set of experiments to completely determine the parameter space of the effective Lagrangian that describes PPS well below the threshold for the creation of electron-positron pairs.

Our results are summarised in figure 2, showing the 95% C.L. exclusion regions that can be obtained with this set of experiments at the present facility HERCULES, without or with multi-crossing, as compared to the current constraint by PVLAS. The predictions of QED and Born-Infeld theory are explicitly indicated. Additional contributions from minicharged particles, or axion-like scalar or pseudoscalar bosons, can sum with them and produce a different point in the ξ_L and ξ_T plane, as discussed in section 2.

Even with the single-crossing version ($F = 1$), figure 2 shows how the PVLAS limits can be substantially improved at HERCULES, possibly allowing for the detection of PPS of non-standard origin. On the other hand, by using a multi-cross mechanism, HERCULES would already be able to detect PPS of QED origin. Note that the result of figure 2 is obtained using the conservative value $F = 30$, corresponding to just $N = 44$ aligned mirrors, which is a more realistic assumption than the maximum value that we have found

above. Finally, in figure 2, we also see how the sensitivity will be improved at ELI in the future, thus allowing for a more precise determination of the parameters.

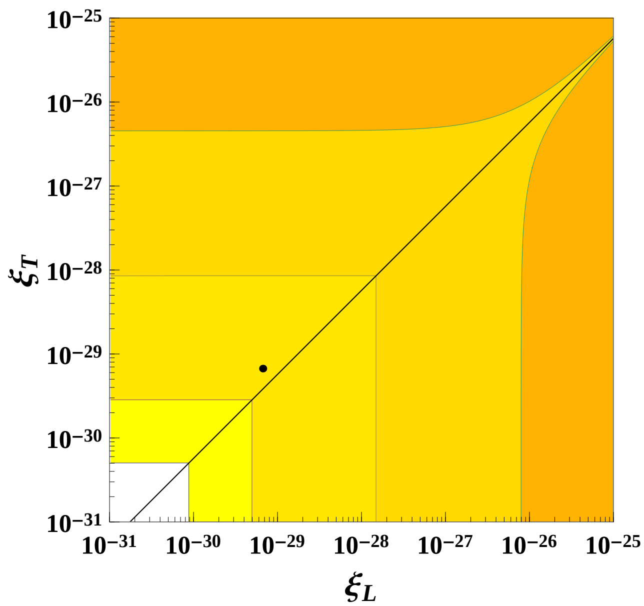

Figure 2: Exclusion plot for the search of PPS. The parameters ξ_L and ξ_T are measured in units of m^3/J. The diagonal line corresponds to Born Infeld theory, while the point is the QED prediction. The darkest region is excluded by the current PVLAS constraint. The next two inner regions correspond to the parts of the parameter space that can be probed at HERCULES with single crossing ($F = 1$) or multiple crossing (choosing $F = 30$), respectively. Finally, the last inner region represents the range that can be reached at ELI with single crossing.

We think that this proposal can eventually contribute to a new class of precision tests of QED and non-standard models, such as Born-Infeld Theory or scenarios involving minicharged particles or axion-like, scalar or pseudoscalar bosons.

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